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Use of Integrated GPS and INS Systems in Aerial Photogrammetry**

1. Introduction

Recent years have been marked by a development of many different land surveying techniques. This has been due to an increased need for reliable and rapidly-delivered information about the subject studied. These new developments pertain not only to the acquisition of data but also, in great degree, to data analysis technologies. Aerial photogrammetry is an excellent example of this. Studies have shown that it is possible to enhance aerial photogrammetry using GPS and INS systems. The use of GPS measurements to determine the centres of image projections "on the fly" and to include them in the aerotriangulation process has become standard. The GPS/INS system also works alongside the electro-optic scanner sensor where it is responsible for the measurement of exterior reference parameters for every image line registered. The integrated GPS/INS system is also responsible for correct spatial placement of the point clouds gathered during aerial laser scanning (ALS). The greatest challenge today is to eliminate the need of use of ground control points and the aerotriangulation process through a sufficiently accurate direct measurement of the camera's exterior orientation parameters during flight. This would reduce costs and produce a less time-consuming process. The method for determining airborne sensor orientation from the measurements instead of from aerotriangulation is called direct georeferencing.

This paper is based on a review of literature including both textbooks and scientific publications. It presents not only an extensive review of the literature but also the author's own remarks regarding the effects which integration of GPS and INS in aerial photogrammetry will bring.

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2. Characteristics of GPS and INS Systems

2.1. GPS Differential System

At present there are two satellite-based systems in use for determining position:

1) the American NAVSTAR GPS,
2) the Russian GLONASS.

In the near future (2013) the European Galileo system will also go into service. Both of the systems mentioned are referred to together as GNSS (Global Navigation Satellite System) in literature. However, the American GPS system is the more popular because it is more widely available and was made accessible (free of charge) to civilian users long before the Russian system. The GPS acronym has, at the same time, become a popular name for all position-determining systems.

One of the branches of technology intended for navigation applications is the DGPS (differential GPS) method. DGPS measurements ensure a high degree of precision in determining the position of the receiver by using data from a reference station. This method in mainly intended to partially or completely eliminate external errors to which GPS receivers are vulnerable (satellite clock error, retardation of the signal in the ionosphere and troposphere, etc.). However, this does not resolve all of the problems. Errors resulting from an unfavourable geometry of the satellites (dilution of position – DOP), noise and the limited resolution of the receiver as well as errors caused by the variable dynamics of the rover receiver persist [7].

The precision with which the position is determined is constant, does not improve over time, and attains a level of 10–20 cm after the application of code smoothing through carrier phase measurement.

The principle limitations of the DGPS method include [1]:

- possible temporal losses of the GPS signal caused by external conditions;
- the requirement that the signal be received from at least 4 satellites at all times during measurement;
- the problem of carrier phase uncertainty;
- loss of accuracy with increased distance from the reference station;
- 1 Hz position refresh frequency – certainly too low for the requirements of aerial photogrammetry.

The use of GPS for in-flight determination of the camera's position has been a fully functional solution for several years now. Particularly, it facilitates the automatisation of the process and increases the reliability of aerotriangulation process while at the same time allowing us to significantly reduce the number of ground control points needed.

2.2. Inertial Navigation System (INS)

The Inertial Navigation System (INS) (Fig. 1) is an independent, autonomous positioning and orientation system which measures acceleration along three orthogonal axes as well as changes in angular tilt of the platform. It is characterised by a high measurement frequency (about 100–200 Hz).

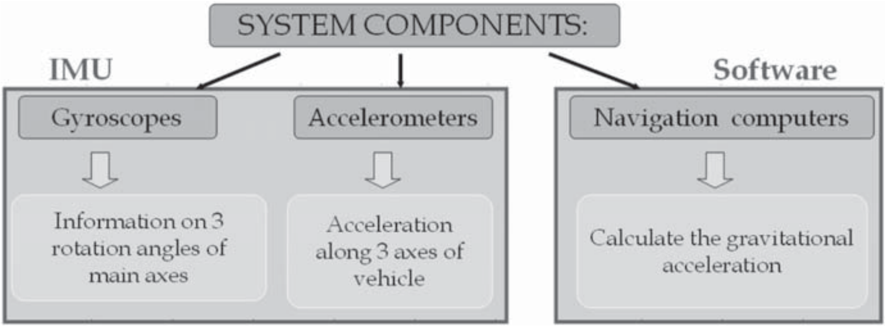

Fig. 1. INS system architecture

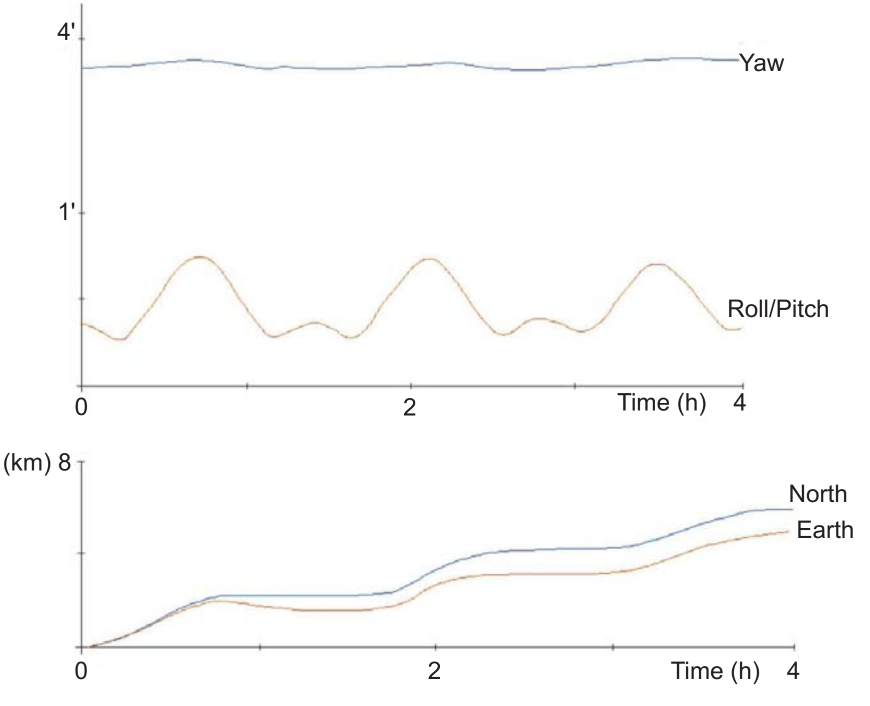

Fig. 2. Simulated navigational accuracy
Source: [12]

In contrast to GPS technology, this system is fully autonomous and, except for the necessary initialisation, does not require any external support. The initialisation period itself depends on external sources, just as with GPS, and is required to determine the initial values of the system's position, velocity and direction in navigational co-ordinates. The current position is determined by calculating displacement relative to the initial position. To determine displacement from the initial position, the INS sensor registers accelerations in the different directions.

A unique characteristic of INS is that it provides accurate but relative positional information. Moreover, the high degree of accuracy is only temporary because it gradually degrades over time (Fig. 2).

This is caused by three main sources of error [12]:
- initial alignment errors (for roll, pitch and yaw angles),
- inertial sensor errors (e.g. gyroscope drift, accelerometer shift),
- computational errors.

3. GPS/INS Integration

The process of creating integrated GPS/INS systems must, in a way, ensure a compromise between high quality and the cost of the system. The most frequent solution is the use of a high-quality GPS receiver with a INS sensor of intermediate quality. Integrated systems are classified according to the degree to which the data from one system complement and support the function of the other.

An initial classification results from the way in which the two sensors are connected, that is from the architecture and function mechanism of the integrated system.

There are four main types of solutions [12]:
- uncoupled systems
- loosely coupled systems
- tightly coupled systems
- deeply or ultra-tightly coupled systems [12].

Uncoupled systems represent the simplest approach to integration which makes it possible to reap the benefits of both a GPS and an INS system, which, however, function independently. The GPS receiver data is used to refresh the INS position at regular time intervals which significantly reduces drift error.

The most common method for integrating GPS and INS is the loosely coupled system, in which each of the sensors possesses its own individual data processing algorithm. With this type of integration, the position, velocity and orientation information registered by the GPS and INS devices are sent to integrated filtering systems where they are compared to each other and the resulting differences are used to achieve more reliable navigational solutions. Characteristics of loosely coupled integration include simplicity, because the architecture of the registering systems is not modified in any way, and a high degree of high reliability [9].

Tightly coupled integration sensors are treated as one system which produces mutually complementary data. This type of integration is characterised by the continuous flow of information between the GPS receiver and the IMU unit. The data from the two sub-systems is transmitted into one filtering unit where it is analysed precisely. In doing so, this system does not require the registration of finished GPS navigational solutions but rather works directly on pseudo-range measurements, carrier wave phases or GPS signal code. These observations are filtered with a Kalman algorithm and are used continuously to model the errors of the IMU unit which leads to a reduction of the growth of INS positioning errors. On the other hand the INS solution supports re-acquisition, that is, the renewal of measurements after a momentary loss of the satellite signal. As a results it is possible for the GPS receiver to function even in less conditions in which fewer than four satellites are visible; it can function even in the case of a signal from only one satellite, although in this case the navigational accuracy decreases rapidly. Tightly--coupled integration is a more reliable method which provides better results than loosely-coupled integration.

The last of the integration methods is deeply-coupled integration. This solution is relatively new and is still in the research and testing phase. The GPS and INS data are analysed using a single Kalman filter. This method, while effective and accurate, has many drawbacks. It requires a very advanced structure of the system itself and it is very demanding in terms of the synchronization of the various sensors with one other [12].

Another type of classification takes into account how the systems are connected with each other and how the data is registered. The filtering process can be centralised or de-centralised depending on how the filter is implemented in the system (Fig. 3).

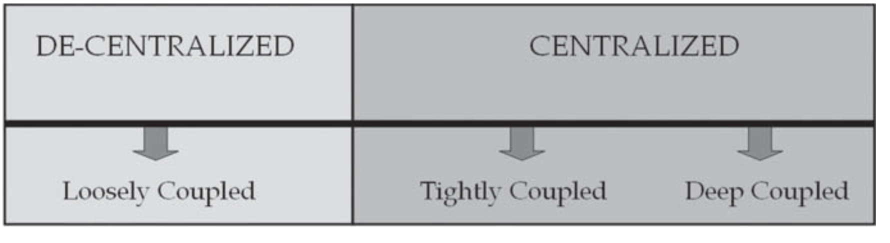

Fig. 3. Types of integration

3.1. Kalman Filter

One of the most important mathematical tools which can be used to obtain an optimal estimation of the state (position, velocity, orientation errors as well as inertial or GPS measurement errors) of the platform is the Kalman filter.

The Kalman filter (Fig. 4) uses the object's dynamics to reduce noise and to achieve a better estimation of the present, past or future position. It works as a recurrent operator. In other words, to estimate the state at a given moment, it only requires the knowledge of the previous state and of the observation vector [8]. It uses all available measurements regardless of the accuracy with which they were made. It is only directed for linear models assuming that the system's internal measurement and processing step within the system have an error of normal distribution [2].

The Kalman Filter algorithm has two fundamental phases in addition to the initialization:

– prediction phase,
– updating phase.

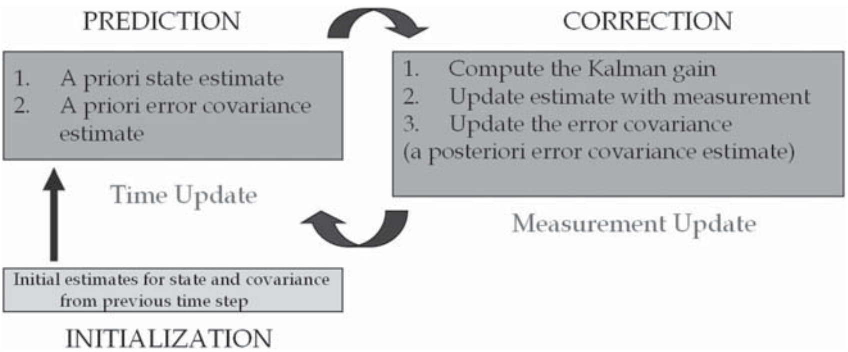

Fig. 4. Algorithm of Kalman Filter
Source: [15]

The prediction phase consists of calculating the next state vector ($k + 1$) and its covariance based on the previous state (k), whereas the updating phase uses current observations to correct and precisely determine the state vector and its covariance [15].

3.2. The Advantages and Disadvantages of Integration

The main reason for integrating GPS and INS systems was the aim of obtaining a synergistic effect. Combining the benefits of the two systems while offsetting and supplementing their deficiencies made it possible to create a more reliable positioning system which, in contrast to a conventional GPS:

– is in a large degree independent of momentary GPS signal loss,
– presents navigational solutions during interruptions in the GPS system,
– determines the vertical ordinate more stable than GPS,
– has a relatively high frequency of data collection (50–250 Hz).

The external orientation parameters determined by the system still exhibit a certain degree of systematic error which sometimes do not make it possible to eliminate aerotriangulation process completely.

The systems other apparent weak points include [10]:

– high dependence on the correct geometry of GPS satellites,
– the necessity for a very precise calibration of the system,
– the quality of the system is strictly dependent on the quality and type of the inertial sensors used,
– instability of one of the sub-systems may cause significant deterioration in the functioning of the other sub-system.

Furthermore, the unpredictable nature of the system's functioning requires numerous additional tests in order to obtain complete control of the entire measurement process.

4. Summary – Directions of Development for Integrated GPS and INS Systems

The use of GPS and INS systems in aerial photogrammetry reveals new horizons for aerotriangulation-connected studies. Both the possibility and the accuracy of the direct georeferencing of the sensors is assessed, as well as the influence of additional data on the results of classic aerotriangulation.

Two different approaches exist at the same time which aim to determine the orientating elements of an aerial photograph based on the data registered by the GPS and INS systems [14]:

– direct georeferencing – the information is obtained "on the fly" solely based on the data from the GPS and INS sensors and without need of use of ground control points
– integration of GPS and INS data and ground control points through the mutual alignment of an image block.

The latter solution ensures the same degree of accuracy as classic aerotriangulation. However, it produces advantages during the data acquisition and data processing stages. It abrogates restrictions regarding the shape of the block (they do not have to be regular) and also, thanks to the known, estimated values of external orientation parameters it makes the aerotriangulation process more efficient by decreasing the number of necessary iterations.

The results of various tests presented in scientific literature show that the accuracy of direct georeferencing is one half to one third as effective as classic aerotriangulation. However, there are instances of studies which produced much more promising results and in which an accuracy for the determination of external orientation elements for the camera was 10 cm for determination of position, 15" for omega and phi orientation angles and 30" for the kappa angle [3–5]. Therefore the determination of complete information about the external orientation parameters of the photograph with a precision near to that of block aerotriangulation becomes possible. This allows us to look with hope to the further development of this type of integration which would, in the future, allow for the complete elimination of ground control points and of the aerotriangulation process.

Doubtless, the integration of GPS and INS systems represents the future of contemporary photogrammetry. However, many more steps must be made in order for this technology to become fully functional and for it to provide high quality data. Especially notable advances that must be made include:

- overcoming the problems related with the detrimental effect of GPS satellite,
- configuration during the flight,
- improving INS technology not only regarding the hardware but also the software,
- eliminating or reducing the effect of drift on an independently functioning set of INS sensors,
- developing more advanced error models for inertial sensors,
- perfecting the integration scheme for both systems and thus their mutual cooperation.

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